

# Radiative Corrections to Kaluza-Klein Masses

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## Outline

- When do I care about radiative corrections?
- Universal Extra Dimensions (bosonic supersymmetry)
  - Bosonic versus fermionic supersymmetry
  - Radiative corrections to KK-partner masses
  - Impact on collider phenomenology of UED
  - Kaluza Klein dark matter
- Summary



## Why radiative corrections?

- The daytime job of a BSM phenomenologist:
  1. Invent a new model beyond SM.
  2. Make sure it is not already ruled out.
  3. Identify discovery signatures.
  4. How well can colliders discriminate from competing models?
  5. How well can colliders measure the new model parameters?
- Are radcors important for those activities?
  1. Every now and then (motivation, HDO, ...)
  2. Usually, unless tree-level effects dominate (LH,  $Z'$ , ...)
  3. Almost never (very few examples)
  4. Probably not.
  5. Yes, to the extent that the activity is important.

$$P_{exp} + \Delta P_{exp} = P_{th} + \delta P$$

As long as  $P_{th}$  is a free parameter, who cares about  $\delta P$ ?

**Exception:**  $P_{th}$  predicted by grand unification, sum rules etc.

As long as  $\Delta P \gg \delta P$ , who cares about  $\delta P$ ?

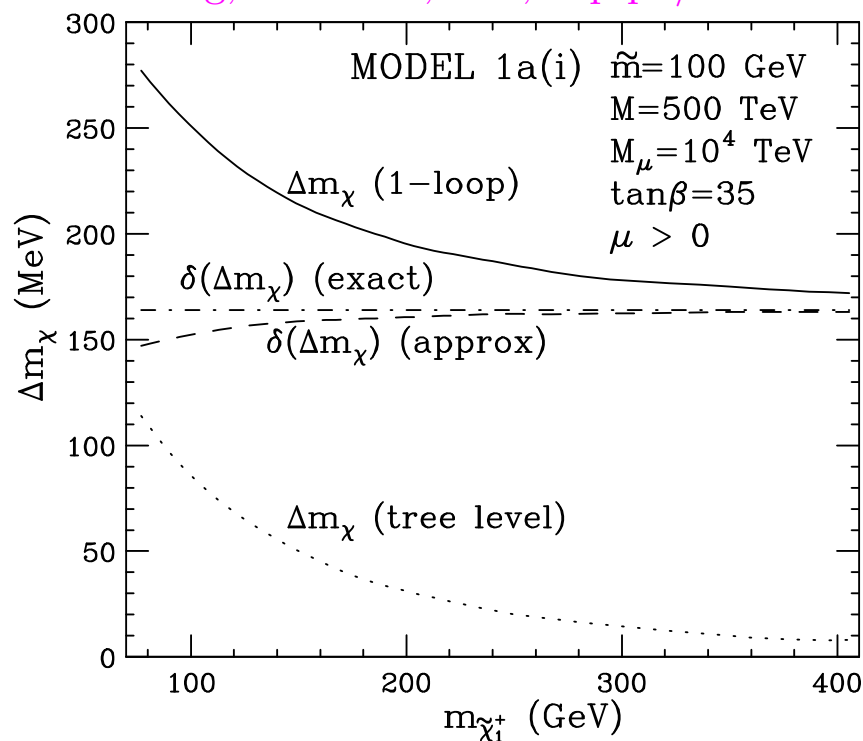
**Exception:** Lepton colliders.



## Impact of radiative corrections on discovery signatures

- Higgs searches in the MSSM (large  $\lambda_b$  corrections affect Higgs branching fractions, production)
- Anomaly mediation (wino mass splitting determines charged wino lifetime)

Cheng, Dobrescu, KM, hep-ph/9811316



- Universal extra dimensions, aka bosonic supersymmetry



## Fermionic extra dimensions (supersymmetry)

- Supersymmetry is an extra dimension theory with new **anticommuting** coordinates  $\theta_\alpha$ :

$$\Phi(x^\mu, \theta) = \phi(x^\mu) + \psi^\alpha(x^\mu)\theta_\alpha + F(x^\mu)\theta^\alpha\theta_\alpha$$

- If  $\psi^\alpha$  are the SM fermions,  $\phi$  are their superpartners (sfermions) with
  - spins differing by 1/2
  - identical couplings
  - unknown masses
- Discovering new particles with those properties **IS** discovering supersymmetry
- $R$ -parity conservation  $\implies$  stable LSP.
- Neutral LSP (neutralinos)  $\implies$  SUSY WIMPs.



## Bosonic extra dimensions (UED, bosonic supersymmetry)

Appelquist, Cheng, Dobrescu, hep-ph/0012100

- Universal Extra Dimensions is an extra dimension theory with new bosonic coordinates  $y$  (spanning a circle of radius  $R$ ):

$$\Phi(x^\mu, y) = \phi(x^\mu) + \sum_{n=1}^{\infty} \phi^n(x^\mu) \cos(ny/R) + \chi^n(x^\mu) \sin(ny/R)$$

- If  $\phi$  is a SM field,  $\phi^n$  and  $\chi^n$  are KK partners with
  - identical spins
  - identical couplings
  - unknown masses of order  $n/R$
- Discovering new particles with those properties IS discovering extra dimensions
- Conservation of  $KK$ -parity  $(-1)^{KK} \Rightarrow$  stable LKP.
- Neutral LKP ( $B_\mu^1$ )  $\Rightarrow$  Kaluza-Klein WIMP.

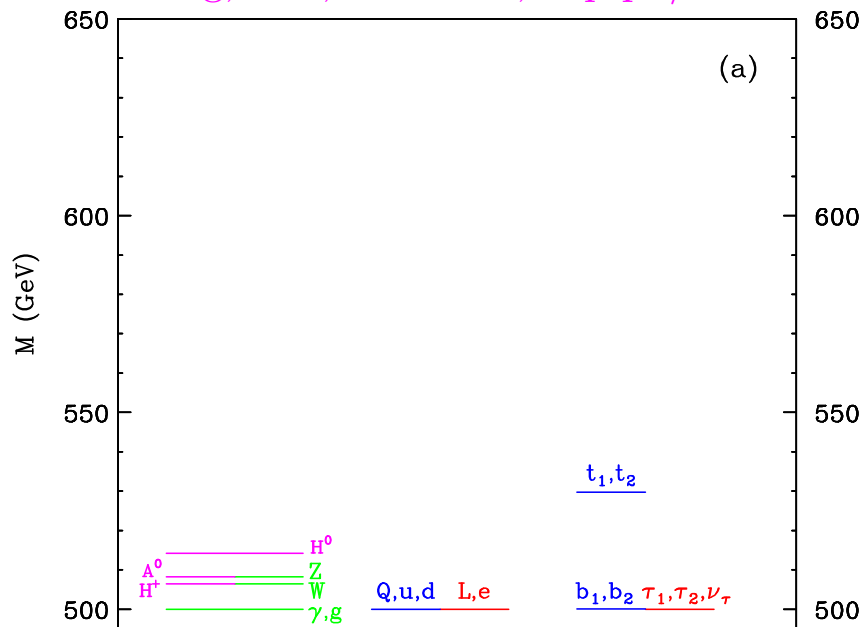


## Tree Level Mass Spectrum

- The tree-level spectrum is extremely degenerate:

$$m_n^2 = \left(\frac{n}{R}\right)^2 + m_0^2$$

Cheng, KM, Schmaltz, hep-ph/0204342



- The radiative corrections are crucial for phenomenology, e.g.

$$e_1 \rightarrow \gamma_1 e_0?$$

$$m_{e_1} - (m_{\gamma_1} + m_{e_0}) \sim -R^{-1} \left( \frac{m_e}{R^{-1}} \right) \sim -R^{-1} 10^{-6}$$

- Lots of stable (charged, colored) heavy particles...



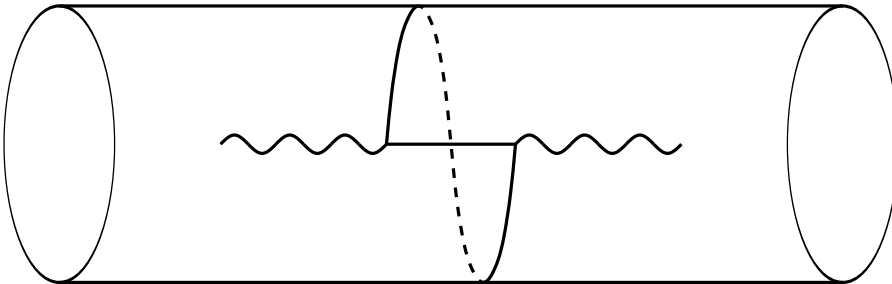
## Radiative corrections to KK masses

- If 5d Lorentz invariance were exact, the KK masses would be fixed by the dispersion relation

$$E^2 = \vec{p}^2 + p_5^2 + m_0^2 = \vec{p}^2 + \left(\frac{n}{R}\right)^2 + m_0^2$$

and the KK mass splittings would only depend on the  $m_0$ 's.

- “Bulk” radiative corrections: 5d Lorentz invariance is broken at long distances by the compactification, loops wrapping around the extra dimension find out about this:



- The corrections are finite and scale with  $R^{-1}$ .

$$\delta m_n \sim R^{-1}$$

- No loss of predictive power! (yet...)





## “Boundary” radiative corrections

- There can be local interactions on the orbifold boundaries which also break 5d Lorentz invariance. In fact, such localized interactions are always generated at one loop, for example

Georgi, Grant, Hailu hep-ph/0012379

$$\frac{\delta(x_5) + \delta(x_5 - \pi R)}{\Lambda} G_4(\mu) F_{\mu\nu}^2$$

- The corresponding corrections to the KK masses are proportional to  $\frac{n}{R}$  and log enhanced:

$$\bar{\delta}m_n \sim m_n \ln \left( \frac{\Lambda^2}{\mu^2} \right)$$

- The “boundary” corrections are larger than the “bulk” corrections and involve many new parameters...

What about predictivity???

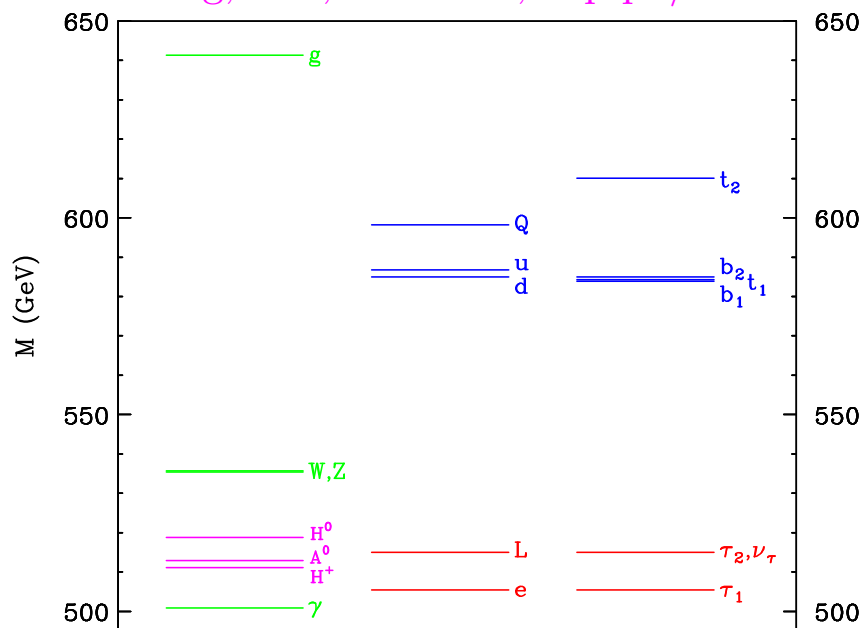
- The usual approach: parameterize our ignorance.
- MUEDs (Minimal Universal Extra DimensionS):  
the boundary terms vanish at the scale  $\Lambda$ .



## Bosonic supersymmetry spectrum

- Including radiative corrections, the mass spectrum of level 1 KK modes looks something like this:

Cheng, KM, Schmaltz, hep-ph/0204342



- Mimics (fermionic) supersymmetry!
- Seems difficult to discover at the LHC, but...
- $W_1^\pm, Z_1$  have pure leptonic branchings!
- $\sin^2 \theta_W^1 \approx 0 \implies \gamma^1 \approx B^1$ , similar to  $\tilde{B}$  in SUSY.



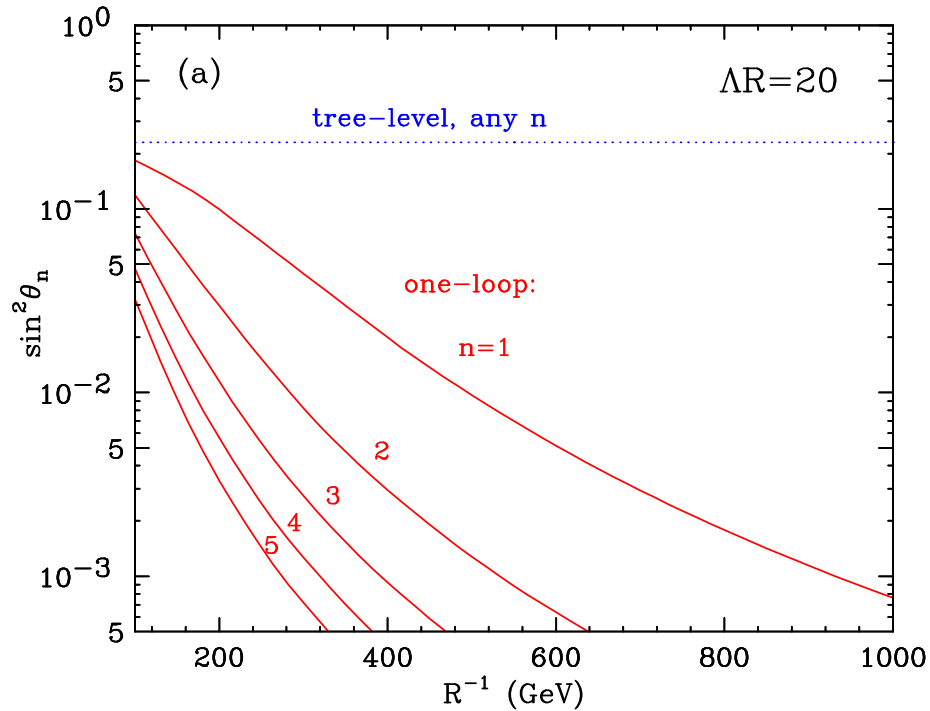
## The KK Weinberg Angle

- Mass matrix for the neutral gauge bosons

$$\begin{pmatrix} \frac{n^2}{R^2} + \frac{1}{4}g_1^2 v^2 + \hat{\delta}m_{B_n}^2 & \frac{1}{4}g_1 g_2 v^2 \\ \frac{1}{4}g_1 g_2 v^2 & \frac{n^2}{R^2} + \frac{1}{4}g_2^2 v^2 + \hat{\delta}m_{W_n}^2 \end{pmatrix}$$

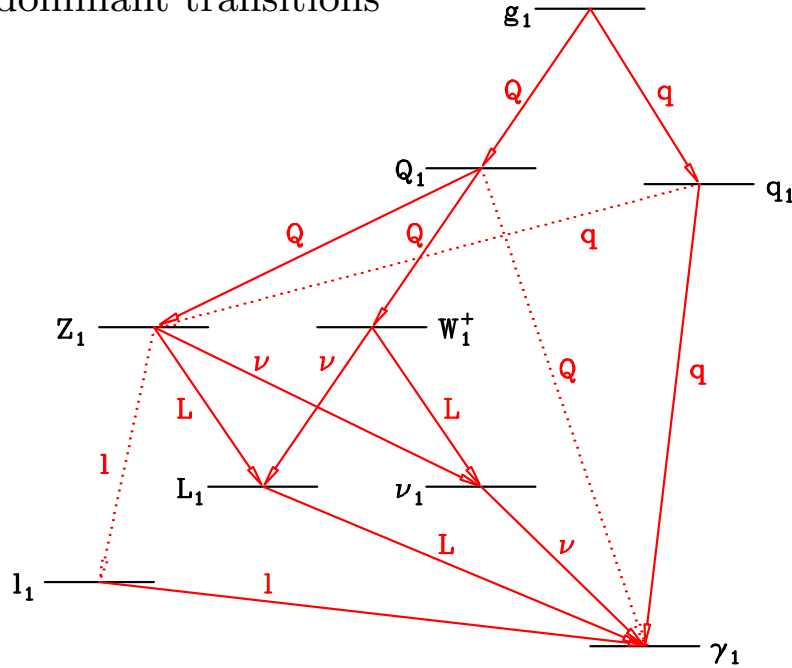
- The Weinberg angle  $\theta_n$  at KK level  $n$ 
  - At tree level: the same for all  $n$
  - At one loop: decreasing with  $n$ , much smaller than  $\theta_0$ .

Cheng, KM, Schmaltz, hep-ph/0204342



## Level 1 Spectroscopy

- Allowed dominant transitions



- KK gluon:  $B(g_1 \rightarrow Q_1 Q_0) \simeq B(g_1 \rightarrow q_1 q_0) \simeq 0.5$ .
- Singlet KK quarks ( $q$ ):

$$B(q_1 \rightarrow Z_1 q_0) \simeq \sin^2 \theta_1 \sim 10^{-2} - 10^{-3}$$

$$B(q_1 \rightarrow \gamma_1 q_0) \simeq \cos^2 \theta_1 \sim 1$$

- KK  $W$ - and  $Z$ -bosons: only leptonic decays!

$$B(W_1^\pm \rightarrow \nu_1 L_0^\pm) = B(W_1^\pm \rightarrow L_1^\pm \nu_0) = 1/6$$

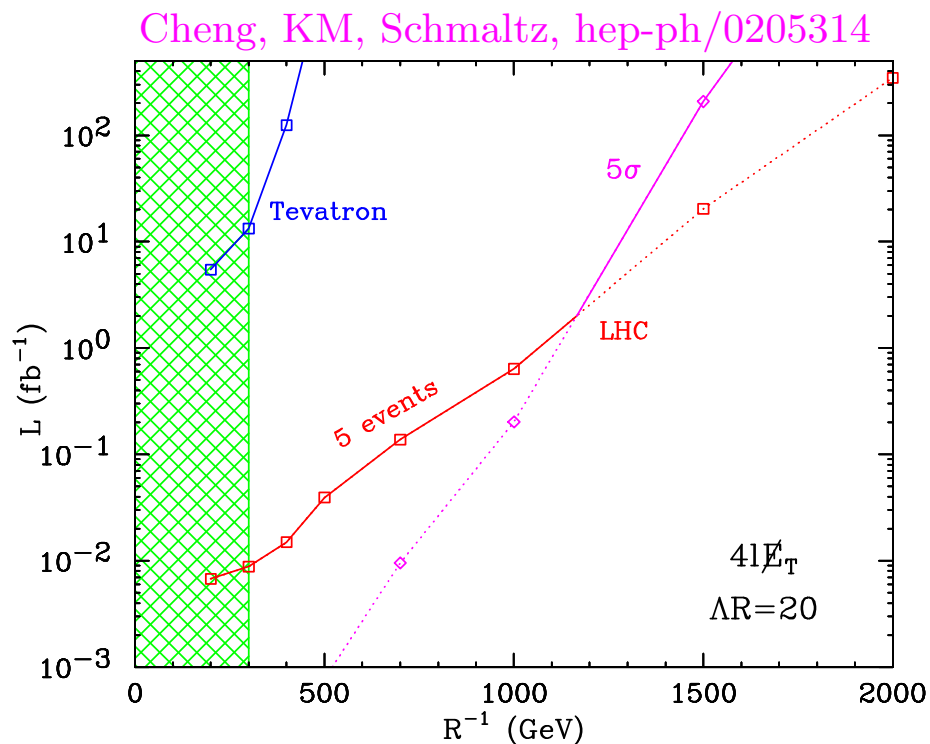
$$B(Z_1 \rightarrow \nu_1 \nu_0) \simeq B(Z_1 \rightarrow L_1^\pm L_0^\mp) \simeq 1/6$$

- KK leptons: 100% directly to the LKP.



## Bosonic supersymmetry discovery reach at the Tevatron and LHC

- Discovery reach in the  $Q_1 Q_1 \rightarrow 4\ell \cancel{E}_T$  channel.

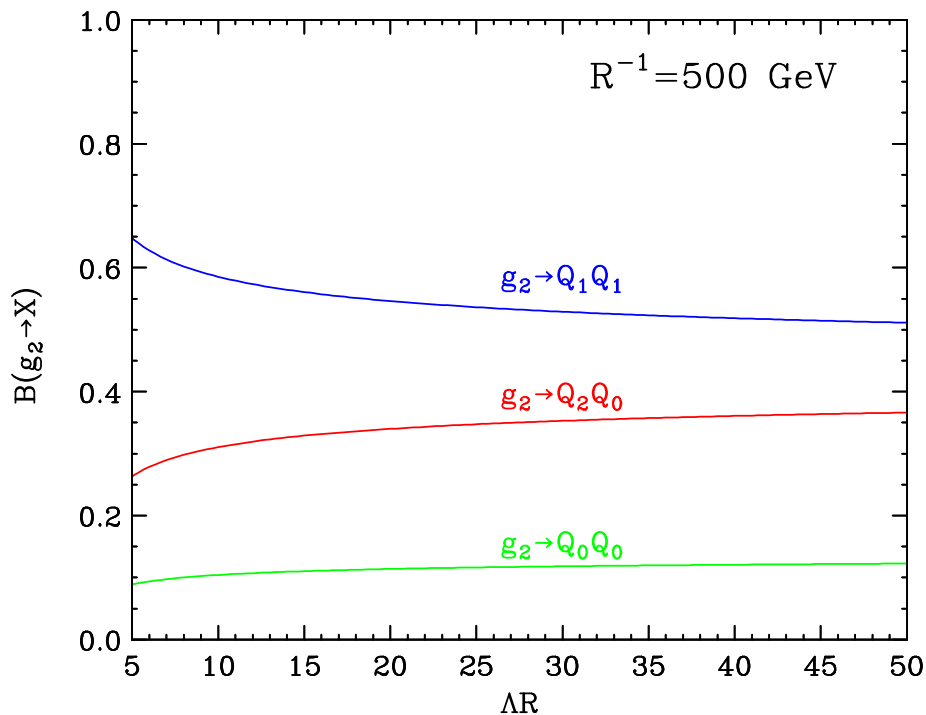


- Typical signatures include:
  - soft leptons, soft jets, not a lot of  $\cancel{E}_T$
  - a lot of missing mass (LHC can't measure it)



## Bosonic or fermionic supersymmetry?

- Can you tell SUSY from UED?
- Yes. Tenth Conference on String Phenomenology in 2011.  
J.Ellis [hep-ph/0208109](#)
- Look for the higher KK levels, e.g.  $2 \rightarrow 20$ ,  $2 \rightarrow 11$ ,  $2 \rightarrow 00$ .
- Single production of KK level 2 is suppressed (involves KK-number violating couplings). Pair production?

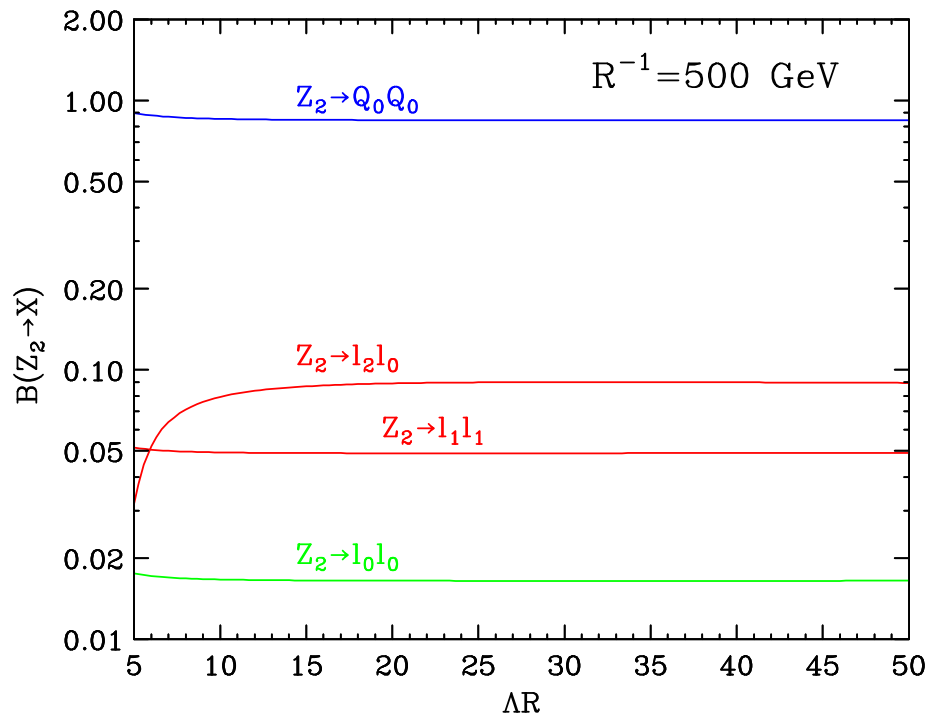


- $g_2$  may appear as a high mass dijet resonance. Coloron?  $Z'$ ?



## Looking for KK level 2

- $Z_2$  appears more promising:  $Z_2 \rightarrow Q_1 Q_1$  and  $Z_2 \rightarrow Q_2 Q_0$  are closed. Lots of leptons? No!
- $Z_2$  branching fractions:

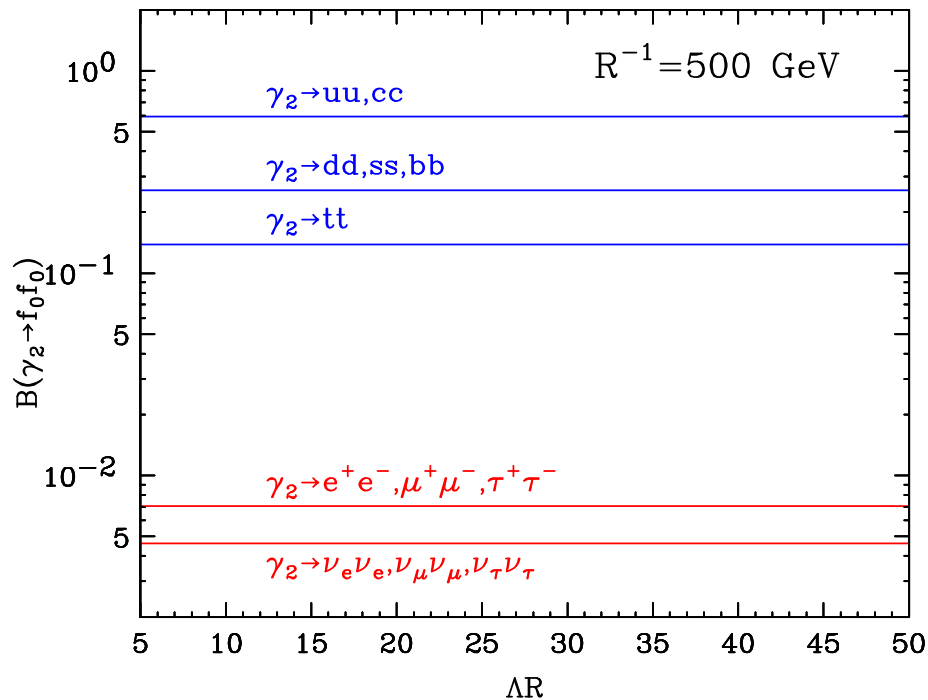


- $Z_2$  also a high mass dijet resonance. Coloron?  $Z'$ ?  $g_2$ ?



## Looking for KK level 2

- $\gamma_2$  appears most promising. All  $\gamma_2 \rightarrow f_2 f_0$  and  $\gamma_2 \rightarrow f_1 f_1$  decays are closed. Every  $\gamma_2$  decay dumps a lot of energy.
- $\gamma_2$  branching fractions:



- $\gamma_2$  **also** a high mass dijet resonance. Coloron?  $Z'$ ?  $g_2$ ?  $Z_2$ ?
- The natural width of level 2 resonances is always negligible compared to the detector dijet mass resolution.

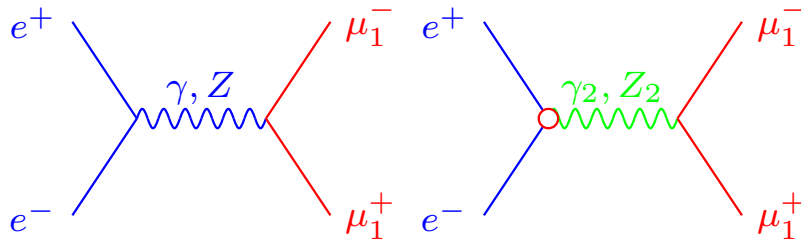
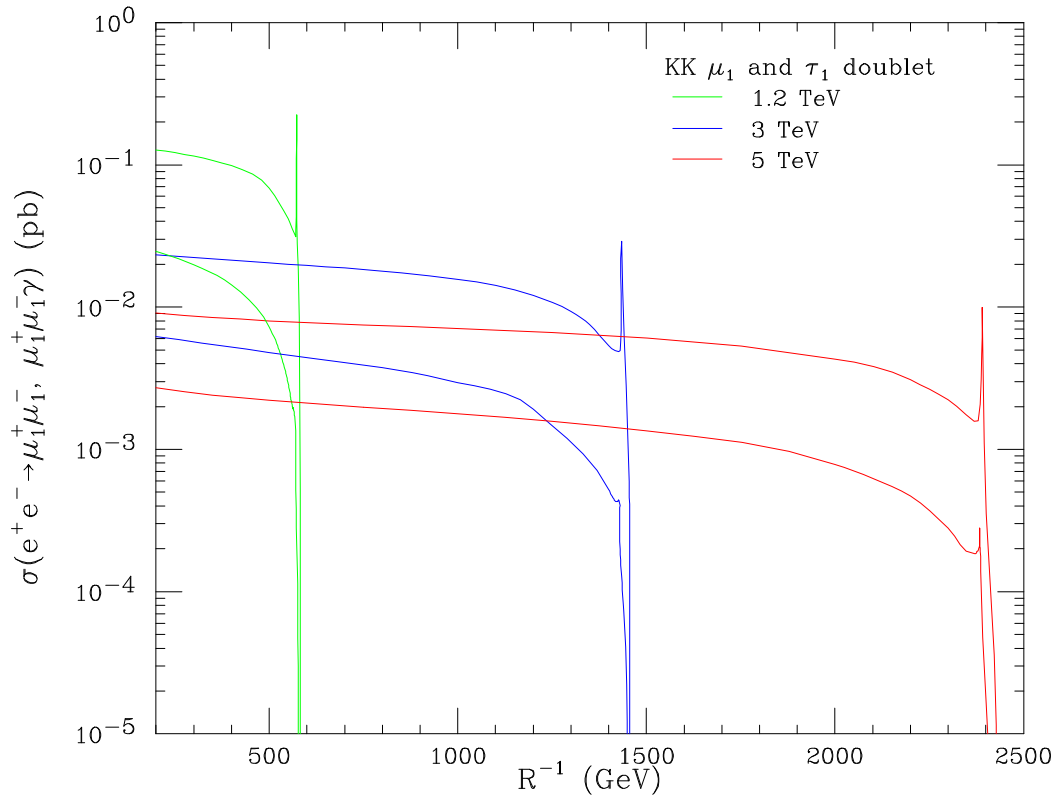




## UED phenomenology: Lepton colliders

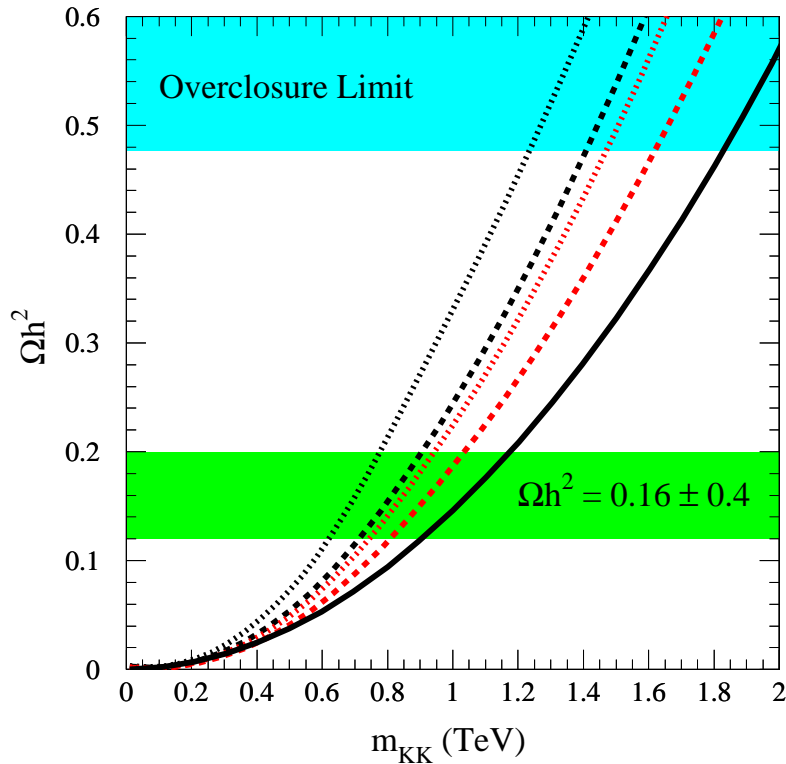
- Implementation of the full UED model in COMPHEP.
- Comparative study of SUSY and UED at LCs under way.

Datta,Kong,KM preliminary



## Kaluza-Klein dark matter

- Relic density: G.Servant, T.Tait, hep-ph/0206071



- Unlike supersymmetry: no helicity suppression

$$\Omega h^2 = \frac{1.04 \cdot 10^9 \text{ GeV}^{-1}}{M_P \sqrt{g_*}} \frac{x_F}{a + 3b/x_F}; \quad x_F = \frac{M_{KK}}{T_F}$$

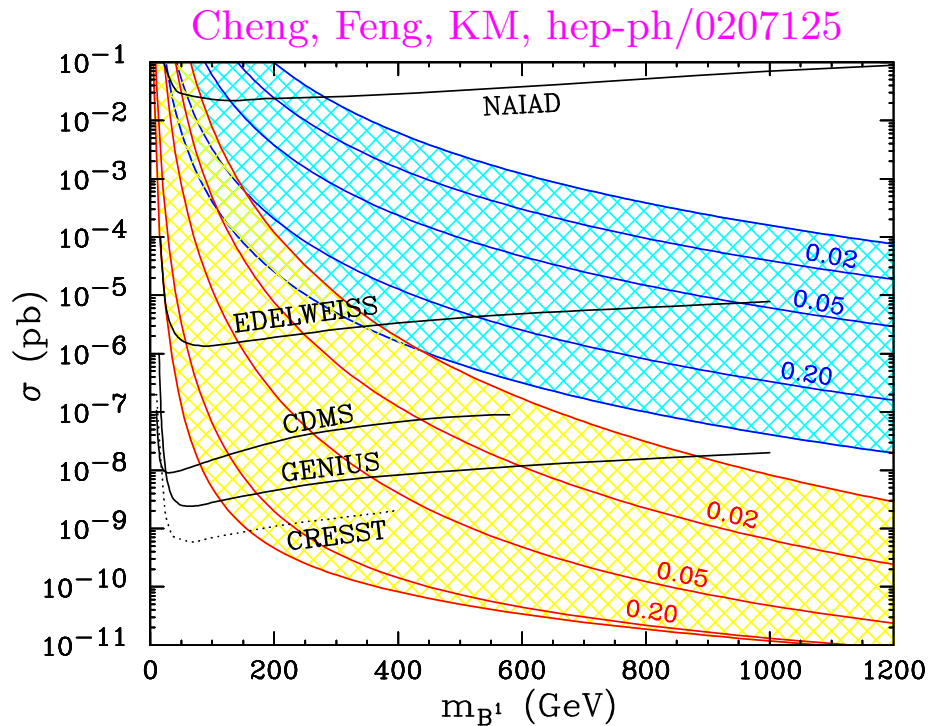
$$a = \frac{\alpha_1^2}{M_{KK}^2} \frac{380\pi}{81}; \quad b = -\frac{\alpha_1^2}{M_{KK}^2} \frac{95\pi}{162}.$$

- Unlike supersymmetry: coannihilation lowers the bound



## KK WIMP Direct Detection

- As usual, spin-dependent and spin-independent cross-sections.



- The signals are enhanced near the  $s$ -channel resonance:  
 $\sigma \sim (m_{q^1} - m_{B^1})^{-2}$ . Unnatural in SUSY, guaranteed here.

Cheng, Feng, KM, hep-ph/0207125

Servant, Tait, hep-ph/0209262

Majumdar, hep-ph/0209277

- Constructive interference: lower bound!



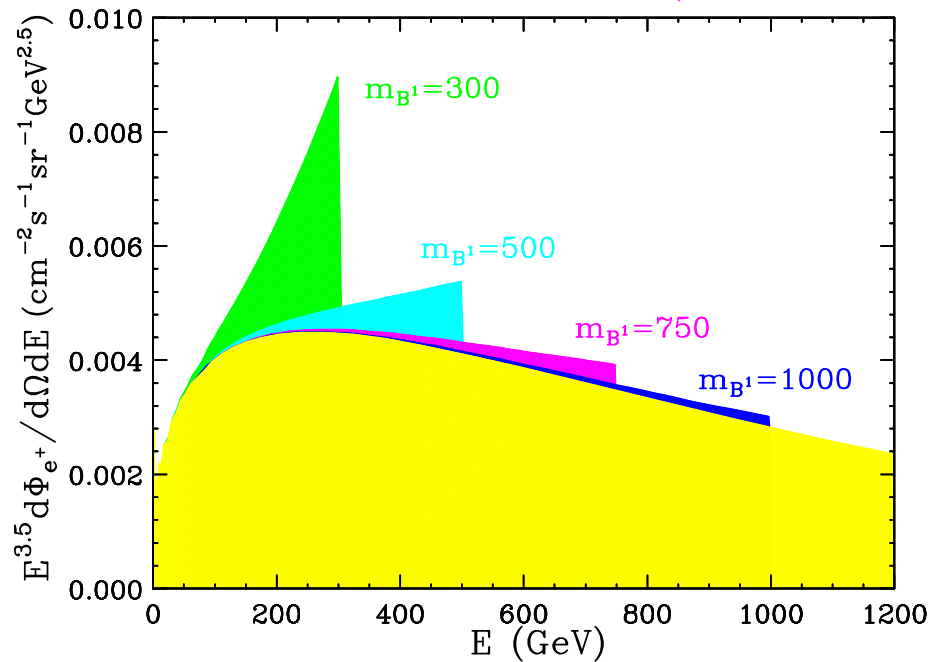
## KK WIMP Indirect Detection: Positrons

- Annihilation into fermion pairs is **not** helicity suppressed.

$$B(B^1 B^1 \rightarrow e^+ e^-) = 20\%$$

- There is a bump! The positrons are monoenergetic at birth. Some smearing from propagation through the galaxy.

Cheng, Feng, KM, hep-ph/0207125



- A smoking gun signal!



## Summary

- The UEDs have interesting phenomenology which for a long time went unnoticed.
- The radiative corrections to the KK mass spectrum drastically change the phenomenology (**discovery signals!**)
- Collider phenomenology – similar to supersymmetry with degenerate spectrum and a stable Bino LSP
  - motivation for studying “degenerate” supersymmetry
  - a strawman model for comparing against SUSY
- The LKP is a good dark matter candidate and offers excellent opportunities for detection.

